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Pullout Resistance of Mechanically Stabilized Earth Wall Steel Strip Reinforcement in Uniform Aggregate

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A wide range of reinforcement-backfill combinations have been used in mechanically stabilized earth (MSE) walls. Steel strips are one type of reinforcement used to stabilize aggregate backfill through anchorage. In the current MSE wall design, pullout capacity of steel strips is evaluated to ensure internal stability of the reinforced mass. The pullout resistance of reinforcement is expressed in terms of pullout resistance factor that measures the reinforcement-backfill interaction. This pullout resistance factor is commonly determined by performing pullout tests.

AASHTO (2012) *LRFD Bridge Design Specifications* provides default values of pullout resistance factor, F*, for strip reinforcement embedded in backfill material with a uniformity coefficient of $C_u \geq 4$, where the uniformity coefficient is defined as the ratio of the particle size at 60% finer to that at 10% finer. However, for backfill with a uniformity coefficient of $C_u < 4$, AASHTO recommends project-specific pullout tests. This AASHTO requirement has disqualified a large amount of aggregates produced in Kansas quarries, or made them difficult and/or costly to be used in MSE wall construction. To address this problem, an experimental study was undertaken in the Geotechnical Engineering Laboratory at The University of Kansas to examine the effect of aggregate uniformity on pullout resistance of steel strips when the uniformity coefficient of aggregate is $C_u < 4$.

Eighteen pullout tests were carried out on ribbed steel strip reinforcements embedded in six aggregate backfills with uniformity coefficients ranging from 1.4 to 14. The pullout resistance of each reinforcement-backfill combination was investigated under three normal stresses to simulate reinforcements placed at different depths of fill. Each test sample was prepared in a consistent way to minimize variations. One of the important influence factors was degree of compaction.

The test results demonstrated that the overall trend for all types of aggregates was similar. The uniform aggregates generally behaved the same way as the well-graded aggregates in terms of pullout resistance. The effect of aggregate uniformity was more obvious in the tests under a lower normal stress than under a higher normal stress. When the normal stress was at 10 psi, there was no obvious effect of aggregate uniformity.

Furthermore, the pullout resistance factors obtained from this study were compared with the default F* values for ribbed strip reinforcement provided by AASHTO (2012). The comparison shows that the pullout resistance factor for ribbed steel strips decreased with depth in the same way as suggested by AASHTO. However, the F* values recommended by AASHTO are conservative as compared with the test results when aggregate backfills with uniformity coefficients ranging from 1.4 to 14 were used. In other words, the F* values recommended by AASHTO can be used to design MSE walls with ribbed steel strips in aggregate backfills with a uniformity coefficient as low as 1.4.

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PREFACE

The Kansas Department of Transportation's (KDOT) Kansas Transportation Research and New-Developments (K-TRAN) Research Program funded this research project. It is an ongoing, cooperative and comprehensive research program addressing transportation needs of the state of Kansas utilizing academic and research resources from KDOT, Kansas State University and the University of Kansas. Transportation professionals in KDOT and the universities jointly develop the projects included in the research program.

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Abstract

A wide range of reinforcement-backfill combinations have been used in mechanically stabilized earth (MSE) walls. Steel strips are one type of reinforcement used to stabilize aggregate backfill through anchorage. In the current MSE wall design, pullout capacity of steel strips is evaluated to ensure internal stability of the reinforced mass. The pullout resistance of reinforcement is expressed in terms of pullout resistance factor that measures the reinforcement-backfill interaction. This pullout resistance factor is commonly determined by performing pullout tests.

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Eighteen pullout tests were carried out on ribbed steel strip reinforcements embedded in six aggregate backfills with uniformity coefficients ranging from 1.4 to 14. The pullout resistance of each reinforcement-backfill combination was investigated under three normal stresses to simulate reinforcements placed at different depths of fill. Each test sample was prepared in a consistent way to minimize variations. One of the important influence factors was degree of compaction.

The test results demonstrated that the overall trend for all types of aggregates was similar. The uniform aggregates generally behaved the same way as the well-graded aggregates in terms of pullout resistance. The effect of aggregate uniformity was more obvious in the tests under a

lower normal stress than under a higher normal stress. When the normal stress was at 10 psi, there was no obvious effect of aggregate uniformity.

Furthermore, the pullout resistance factors obtained from this study were compared with the default F* values for ribbed strip reinforcement provided by AASHTO (2012). The comparison shows that the pullout resistance factor for ribbed steel strips decreased with depth in the same way as suggested by AASHTO. However, the F* values recommended by AASHTO are conservative as compared with the test results when aggregate backfills with uniformity coefficients ranging from 1.4 to 14 were used. In other words, the F* values recommended by AASHTO can be used to design MSE walls with ribbed steel strips in aggregate backfills with a uniformity coefficient as low as 1.4.

Acknowledgements

This research project was financially sponsored by the Kansas Department of Transportation (KDOT) through the Kansas Transportation Research and New-Developments (K-TRAN) Program. Mr. James J. Brennan, the Chief Geotechnical Engineer of KDOT, was the monitor for this project. Bonner Spring Quarry APAC-Kansas City, Inc., provided the aggregate materials used in this study, and Mr. Kyle E. Harbour, Quality Control Manager, with his staffs provided great assistance in the selection and collection of aggregate materials. The laboratory manager and technicians, Matthew Maksimowicz, David Woody, and Erick Nicholson, in the Department of Civil, Environmental, and Architectural Engineering (CEAE) at The University of Kansas (KU) provided their technical support during the fabrication of the new pullout box and laboratory pullout testing. Furthermore, graduate students Ghaith Abdulrasool, Jun Guo, Yan Jiang, and Fei Wang from the KU CEAE Department provided their assistance in collecting aggregate materials from the quarry and performing laboratory experiments.

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Chapter 1: Introduction

This chapter provides general background of soil reinforcement and composition, as well as the design of mechanically stabilized earth (MSE) walls. It also covers the problem statements, objective of this research, and methodology adopted, as well as the organization of this report.

1.1 Background

Elias, Christopher, and Berg (2001) provided the historical development of MSE wall systems, which is summarized below. A variety of materials have been used to improve soil since the ancient time. Tree branches were used as soil reinforcement in dikes of earth in China for at least 1,000 years, and along the Mississippi River in the 1880s. Wooden pegs and bamboo or wire mesh are other materials that have been used for erosion protection and landslide mitigation in history. During medieval times, people used alternating layers of earth and logs for building fortifications. In the early 1900s, layers of metallic reinforcements were embedded in soil to reinforce the downstream slopes of earth dams. In the early 1960s, the development of the modern soil reinforcement system by Henri Vidal led to the establishment of Reinforced Earth®. This system uses steel strip reinforcement.

The primary function of reinforced soil mass is to enhance the mechanical properties (especially tensile strength) of soil by placing reinforcement layers. In other words, the reinforced soil mass behave similarly to reinforced concrete. The use of MSE wall has become widely accepted, as it is a cost effective technology. The term MSE wall is generally used to describe the earth retaining systems that are constructed by adding layers of reinforcing elements into soil.

An MSE wall constructed on a foundation has four main components, namely a facing unit, reinforcing elements, reinforced backfill, and retained soil. Common types of soil reinforcing elements are steel strips, welded steel grids, geogrids, and geotextile sheets. A wide range of materials used as facing units include precast concrete panels, dry cast modular blocks, welded wire mesh, wrapped-around geosynthetics, and gabions (Elias et al., 2001). The select soil material placed within the reinforcement zone is referred to as reinforced backfill. In situ soil or backfill material placed directly behind the reinforced zone is termed as a retained soil. Figure 1.1 shows the main components of a typical MSE wall system.

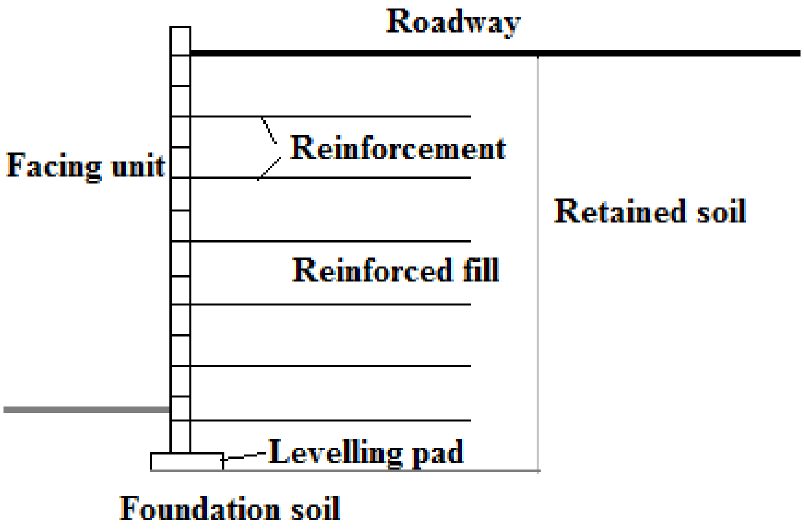


Figure 1.1: Main Components of a Typical MSE Wall

MSE wall systems have been used for different applications, such as retaining walls, bridge abutments, wing walls, access ramps, and waterfront walls. The ease and speed of construction, economy, ability to tolerate differential settlement, and aesthetics are the main advantages of MSE walls, which have made them an attractive option. Figure 1.2 shows a few applications of MSE walls.

Figure 1.2: MSE Wall Applications
Source: The Reinforced Earth Company, n.d.

The design of MSE walls has been mostly based on limit equilibrium analysis, where external and internal stability are required to ensure the overall stability of the MSE wall. External stability focuses on the structural integrity among the main wall components, which act coherently as one unit. This analysis ensures that the MSE wall has sufficient factors of safety against potential failure modes, such as sliding, overturning, bearing, and global failure. In addition to the external stability, internal stability analysis is needed to ensure the MSE wall has sufficient factors of safety against rupture and pullout of reinforcement and connection failure between reinforcement and wall facing. Pullout tests have been commonly used to evaluate reinforcement pullout resistance from soil.

1.2 Research Problem Statement

MSE walls have been commonly used in Kansas to support bridge abutments, sound barrier walls, and other structures. Within MSE walls, steel strips are often used as reinforcement to stabilize aggregate backfill through anchorage. The anchorage capacity of strip reinforcement depends on its tensile strength and pullout resistance in aggregate. The pullout resistance of strip reinforcement is dependent on the pullout resistance factor between strip reinforcement and aggregate. AASHTO (2012) design guidelines provide a formula to estimate the pullout resistance factor for strip reinforcement in aggregate with a uniformity coefficient of $C_u \geq 4$, where the uniformity coefficient is defined as the ratio of the particle size at 60% finer to that at 10% finer. AASHTO design guidelines require pullout tests to determine the pullout resistance factor of strip reinforcement in aggregate with a uniformity coefficient of $C_u < 4$.

This requirement has resulted in the disqualification of a large amount of aggregate produced by the quarries in Kansas for MSE wall construction. If the aggregate is re-processed to meet the uniformity requirement, the cost of aggregate will be increased. Alternatively, pullout tests of strip reinforcement can be performed to determine the pullout resistance factor. Unfortunately, no commercial laboratory is readily available in Kansas to provide such pullout testing service. Strip reinforcement and aggregate have to be sent to a couple of specialty laboratories in the nation, which will increase the cost and potentially delay construction. Therefore, there is a great need to verify the existing AASHTO (2012) pullout resistance formula for Kansas aggregates with a coefficient of uniformity less than 4, or to develop a new formula that is applicable to these aggregates.

1.3 Research Objective

The objective of this research was to evaluate the pullout resistance of steel strip reinforcement embedded in aggregate with a uniformity coefficient of $C_u < 4$ and verify the existing AASHTO (2012) pullout resistance formula for Kansas aggregates, or to develop a new formula that is applicable to these aggregates. Therefore, a series of pullout tests were conducted with Kansas aggregates of different uniformity coefficients in the Geotechnical Engineering Laboratory at The University of Kansas.

1.4 Research Approach

This research first identified potentially usable aggregates and steel strip reinforcement in Kansas. Six types of aggregates with different uniformity coefficients from the quarries in Kansas and one type of ribbed steel strip reinforcement from the manufacturer, Reinforced Earth®, were collected. To determine the gradations of the aggregates, sieve analyses were conducted using the large sieve machine, and the uniformity coefficients were calculated for all types of aggregates. Additionally, the angle of friction for each type of aggregate was determined using large triaxial shear tests in the Geotechnical Engineering Laboratory at The University of Kansas. Standard density tests were conducted to obtain the minimum and maximum dry densities of all aggregates. After the physical characteristics of the aggregates were identified and confirmed, pullout tests were performed on strip reinforcement embedded in these aggregates at three different normal stresses. Finally, pullout test data were analyzed to estimate the pullout resistance factors of the steel strip reinforcement embedded in six different aggregate backfills under normal stresses.

1.5 Report Organization

This report includes six chapters. Chapter 1 presents a brief introduction to this study, which comprises background, problem statement, research objective, research methodology, and report organization. Chapter 2 provides the literature review on past research work related to this study, which includes stress transfer mechanisms in MSE walls, guidelines for pullout resistance determination, and both laboratory and field pullout testing performed by others. Chapter 3 discusses the test materials and apparatus. Chapter 4 describes the test procedures and data acquisition system used in this study. The test results and data analyses are discussed in Chapter 5 of this report. Chapter 6 presents the conclusions and recommendations based on the test results and analyses.

Chapter 2: Literature Review

As explained in Chapter 1 of this report, people have long realized that adding appropriate reinforcing elements into soil can increase soil resistance. The modern soil reinforcement technology was developed as Reinforced Earth 5 decades ago. Mechanically stabilized earth (MSE) wall was part of this development. With increasing demand for MSE wall applications, numerous researchers have conducted research on the MSE wall, including the pullout resistance of reinforcement. Pullout tests have been commonly adopted to investigate the factors that govern pullout resistance of reinforcement in soil.

This chapter presents a literature review on related research work done by others in the past, including the mechanisms that govern the interaction between soil and reinforcement, the standard guidelines for estimating pullout resistance in the absence of pullout test results, and past laboratory and field pullout tests relevant to this study.

2.1 Stress Transfer Mechanism

French architect and engineer Henri Vidal was credited for the development of the modern soil reinforcement technology in 1960s (Elias et al., 2001). Vidal (1969) recognized that the capability of an earth mass to withstand tensile stresses can be enhanced by embedding strip reinforcements. He realized that the bond developed within the reinforced earth arises from the friction between the reinforcing element and particles. Hence, he recommended that proper bonding is required at the soil-reinforcement interface so that slippage will be avoided.

Several investigations have been carried out on alternative soil reinforcement materials other than steel strip reinforcement. As a result, the welded wire soil reinforcement was introduced and later gained widespread applications. Chang, Hannon, and Forsyth (1977) performed experimental tests to evaluate the pullout resistance of strip and welded wire mesh-type reinforcements. This study reported that plain bar-mesh reinforcement resulted in pullout resistance approximately six times that of strip-type reinforcement with the same reinforcement surface area in gravely sand soil. Peterson (1980) performed a comprehensive study on the mechanisms that govern the pullout resistance of welded wire mesh. He found two separate mechanisms contributing to the pullout resistance in welded wire mesh, which are *friction* between longitudinal wires and soil particles and *anchorage* of transverse wires embedded in the soil.

The FHWA manual stated that the stress transfer mechanism between soil and reinforcement is governed by friction and/or passive resistance, depending on reinforcement geometry (Elias et al., 2001). Friction develops at the locations where relative shear displacement occurs between the reinforcement surface and backfill soil. Steel strips, longitudinal bars of welded steel grids, geotextiles, and geogrids have reinforcing elements that generate pullout resistance through friction. Passive resistance occurs through the development of bearing-type stresses on reinforcing elements oriented normal to the direction of movement. Passive resistance is generally considered to be the primary resistance for rigid geogrids and wire mesh reinforcements. The transverse ridges on ribbed strip reinforcement also provide some passive resistance. Figure 2.1 illustrates the frictional and passive resistance mechanisms of the ribbed steel strip reinforcement under pullout force.

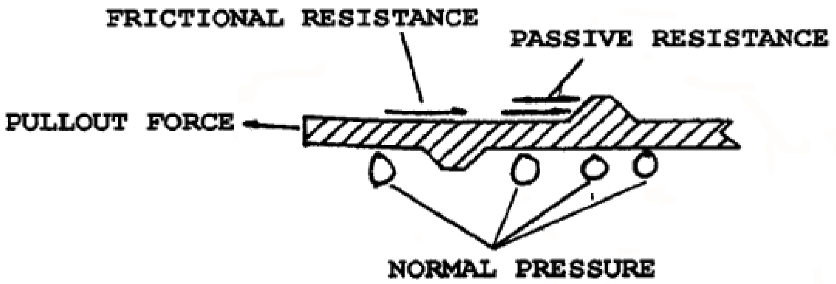


Figure 2.1: Pullout Resistance Mechanism on Ribbed Strip Reinforcement
Source: Elias et al., 2001

Moreover, the reinforcement characteristics that affect the contribution of each transfer mechanism include surface roughness, normal effective stress, grid aperture, thickness of transverse members, and elongation characteristics of the reinforcement. Equally important for interaction development are the soil characteristics, which include grain size, grain size distribution, particle shape, density, water content, cohesion, and stiffness (Elias et al., 2001).

2.2 Guidelines for Pullout Resistance Determination

The ultimate tensile load required to generate the outward movement of the reinforcement through the reinforced soil mass is defined as the pullout resistance of reinforcement. Several approaches and design equations have been established and are currently used to estimate the pullout resistance by considering frictional and/or passive resistance. Elias et al. (2001) introduced a definition of pullout resistance based on a pullout resistance factor, F*. This single parameter F* combines the contribution of the two separate stress transfer mechanisms to pullout resistance. According to the AASHTO (2012) *LRFD Bridge Design Specifications* or the FHWA manual (Elias et al., 2001), the pullout resistance, P_r, of the reinforcement per unit width of reinforcement is calculated using the following generalized Equation 2.1:

$$P_r = F^* \alpha \sigma_v C L_e \qquad \textbf{Equation 2.1}$$

Where:

L_e = length of reinforcement in the resisting zone

F* = pullout friction factor

α = scale effect correction factor (for steel reinforcement, α =1)

σ_v = vertical overburden stress at the reinforcement level

C = overall reinforcement surface area geometry factor based on the gross perimeter of the reinforcement (equal to 2 for strip, grid, and sheet-type reinforcements)

Generally, it is more reliable to evaluate the pullout resistance of reinforcement in backfill material used in a specific project by conducting pullout tests. However, it may practically not be possible to perform pullout tests, as the specific backfill source may not be known at the time of wall design. Thus, in common design practice, the pullout resistance of reinforcement is estimated using the pullout resistance factor, F*. The AASHTO (2012) *LRFD Bridge Design Specifications* provides default values of pullout resistance factor F* for standard backfill materials with a uniformity coefficient of $C_u \geq 4$. In the absence of site specific pullout test data, the semi-empirical relationships in Figure 2.2 may be used to estimate the pullout resistance factor, F*, which can be used to calculate pullout resistance of reinforcement for internal stability analysis of walls.

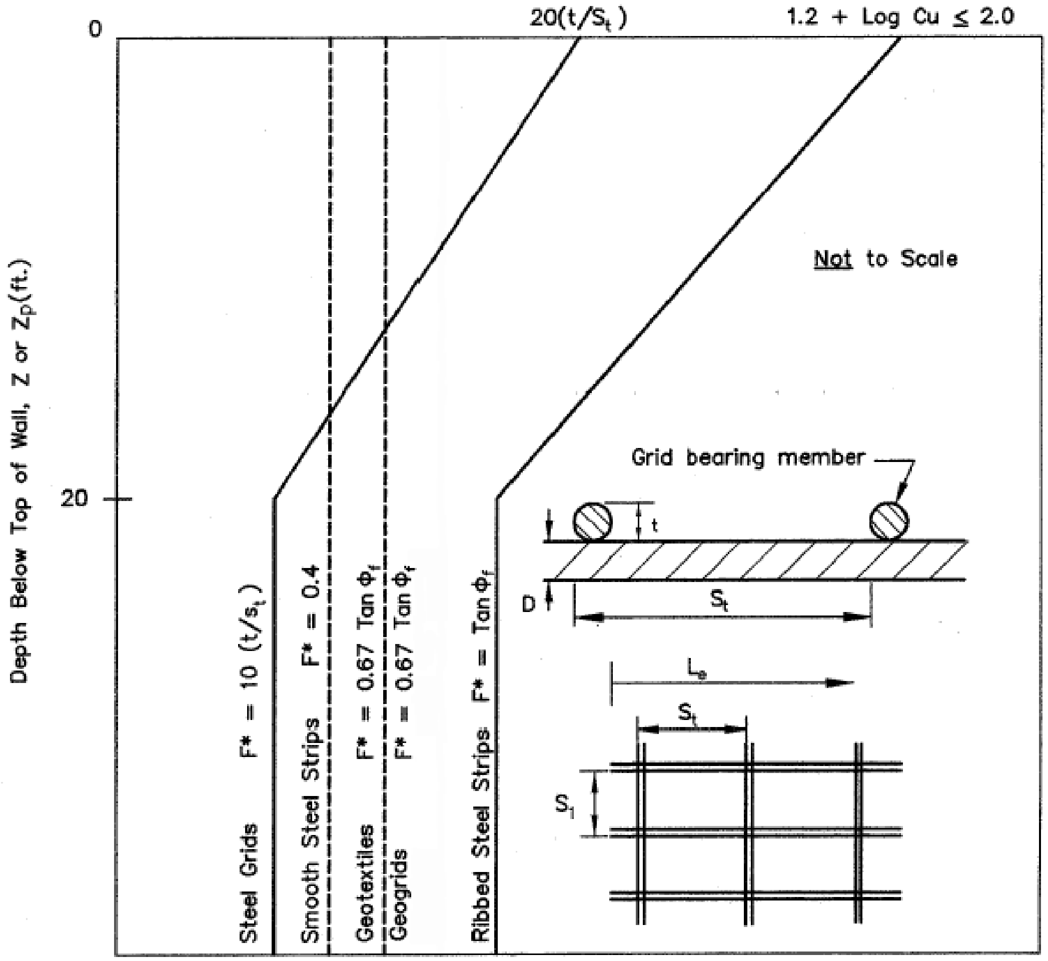


Figure 2.2: Default Values for Pullout Resistance Factor, F*

Source: AASHTO, 2012

The pullout resistance factor, F*, for steel ribbed reinforcement can be estimated as follows:

$$F^* = tan\rho = 1.2 + logC_u \leq 2 \; at \; the \; top \; of \; the \; wall$$ **Equation 2.2**

$$F^* = tan\phi \; at \; a \; depth \; of \; 20ft$$ **Equation 2.3**

Where:

C_u = the uniformity coefficient of the backfill

ϕ = the angle of internal friction of the backfill

If the specific C_u for the backfill is unknown at the time of MSE wall design, a C_u of 4 should be assumed (i.e., F* = 1.8 at the top of the wall) for backfill meeting the AASHTO (2010) requirements.

2.3 Past Pullout Tests

The following sections summarize the laboratory and field pullout tests performed by others in the past.

2.3.1 Laboratory Pullout Tests

A number of laboratory tests have been performed to evaluate the pullout resistance of inextensible metallic (steel) and extensible (geosynthetic) reinforcements from soil. Jayawickrama, Surles, Wood, and Lawson (2013) provided a summary of literature review on 22 laboratory pullout tests performed on inextensible metallic reinforcements in their Texas Department of Transportation (TxDOT) Project 0-6493. According to this literature summary, the backfill materials used in the pullout tests ranged from silt and weathered clay with low plasticity to granular soil or crushed stone. However, most of the laboratory tests used granular soils as backfill.

The test data for ribbed steel reinforcement from past laboratory pullout tests are limited. Table 2.1 presents the summary of the laboratory pullout tests conducted on steel strip reinforcements embedded in granular backfill. Table 2.1 was modified from that in Jayawickrama et al. (2013). Although some of the pullout tests investigated different types of reinforcements at the same time, information related to strip reinforcement is included in Table 2.1.

Table 2.1: Summary of Past Laboratory Pullout Tests

Reference	Backfill	Reinforcement	Pullout box	Normal Stress (psf)	Pullout Load
Chang et al. (1977)	Poorly-graded gravelly sand	Steel strip: 2.3 inches wide, 0.125 inches thick, and 54 inches long	36 inches wide, 54 inches long, and 18 inches high	1440 (by hydraulic jack)	Applied by a hydraulic jack at a constant strain rate of 0.002 inches/min
Lee and Bobet (2005)	Clean sand and silty sand	Steel strip: 2 inches wide, 0.120 inches thick, and 30 inches effective length	Two chambers: (a) soil chamber of 1.31 ft wide, 3.28 ft long, 1.64 ft high; and (b) water chamber*	627, 2089, and 4177 (by air bag)	Applied by an electric hydraulic ram at a strain rate of 0.04 inches/min for drained and 0.39 inches/min for undrained tests
Rathje et al. (2006)	Crushed concrete and recycled asphalt pavement aggregate	Ribbed steel strip: 2 inches wide, 18 inches long, about 0.16 inches thick, and 0.12 inches high ribs	20 inches wide, 20 inches long, and 13.5 inches high	209 to 2715 (by air bag)	Applied by a pneumatic piston with a strain rate of 0.04 inches/min
Jayawickrama et al. (2013)	Type A and Type B**	Ribbed steel strip: 2 inches wide, 4 ft, 6 ft, 8 ft, and 12 ft long, and 0.157 inches thick.	12 ft wide, 12 ft long, and 4 ft high	551 to 5667 (by hydraulic jack)	Applied by a hollow core hydraulic jack at a strain rate ranging 0.05 to 0.23 inches/min

*Water chamber is a box for water supply to saturate the soil and maintain constant water pressure in the soil chamber during pullout testing.

**Type A: gravelly backfill with uniformity coefficient of 12-180, which is classified as GW/GP/GP-GM. Type B: sandy backfill with uniformity coefficient of 4.4-7.0, which is classified as SP-SM (Jayawickrama et al., 2013; Lawson, Jayawickrama, Wood, & Surles, 2013).

Table 2.1 shows that all the pullout tests were carried out on strip reinforcements embedded in granular soils, except the test conducted by Rathje et al. (2006), in which crushed concrete and recycled asphalt pavement aggregate were used as backfill. According to Jayawickrama et al. (2013), in most of the tests, no adequate information was given on whether these backfill materials satisfied the gradation requirements set by the AASHTO (2010) *LRFD Bridge Construction Specifications*. The backfill materials used by Jayawickrama et al. marginally satisfied the requirements for MSE wall select backfill as specified in the AASHTO specifications. Also, in their study, the uniformity coefficients were provided for each backfill material. The test performed by Rathje et al. primarily aimed at investigating the suitability and sustainability of crushed concrete and recycled asphalt pavement aggregate to be used as MSE wall backfills, not the internal stability of the backfill-reinforcement mass. Although Jayawickrama et al. performed the pullout tests on two types of backfill materials (Types A and B), the main objective of their study was to determine pullout resistance factors applicable to specific backfill-reinforcement combinations used by TxDOT. Therefore, none of the above tests focused on investigating the effect of backfill material gradation on the pullout resistance of the reinforced mass. Furthermore, most of the past research work was performed either on backfill materials with a uniformity coefficient of >4 or backfill without gradation information.

Different sizes of test boxes were used in the above pullout tests. The smallest test box was the one used by Rathje et al. (2006), with dimensions of 20 inches wide × 20 inches long × 13.5 inches high, whereas the largest test box used by Jayawickrama et al. (2013) and Lawson et al. (2013) had dimensions of 12 ft wide × 12 ft long × 4 ft high. Inflated air bag and hydraulic jack against a reaction frame are two common ways used to simulate the overburden stresses. In the above tests, except the tests by Rathje et al., a hydraulic jack was used to apply the pullout load.

As part of their literature review, Jayawickrama et al. (2013) presented the relationship of the pullout resistance factors, F*, versus depth of fill based on the data obtained from past laboratory pullout tests on strip reinforcement embedded in granular soils. Even though most of the data points lie to the right side of the AASHTO reference line, a few of them were plotted to the left of the reference line. Once again, it should be noted that there was no sufficient information about whether the backfill materials used in most of the tests met the gradation requirements specified by AASHTO. Laboratory pullout tests performed by Jayawickrama et al. showed that the pullout resistance factors, F*, for ribbed strip reinforcements embedded in granular backfill are considerably higher than the default F* values provided by AASHTO. Moreover, the pullout resistance factors, F*, for ribbed strip reinforcements embedded in the gravelly backfill (Type A) were found to be significantly higher than those embedded in the sandy backfill (Type B).

2.3.2 Field Pullout Tests

Limited field pullout tests have been conducted to determine steel strip pullout resistance. Chang et al. (1977) carried out field tests on pullout resistance of strip reinforcement embedded in decomposed granite in a reinforced earth wall constructed in California on Cal-39 in the San Gabriel Mountains. The summary of this field study is presented in Table 2.2.

Table 2.2: Field Pullout Testing

Backfill	Reinforcement	Depth of fill	Pullout load
Decomposed granite	Galvanized steel strips of 2.362 inches wide, 5, 10, 15, 23, and 46 ft long, and 0.118 inches thick; additional dummy steel strips used.	5,10, and 15 ft long strips embedded at depths of 7.5, 12.4, and 18.2 ft, respectively; three 23 and 46 ft long strips at depths of 18 and 38 ft, respectively.	No details provided

Source: Chang et al., 1977

In this study, smooth steel strips were used instead of ribbed strips. According to Jayawickrama et al. (2013), most of the pullout resistance factors, F*, estimated based on the field test data were higher than the default values provided by AASHTO (2012). However, some of the field measured F* lie to the left of the reference line for smooth steel strips recommended by AASHTO.

Chapter 3: Test Materials and Apparatus

This chapter describes the test materials and the test apparatus used in this study, including the characteristics and specifications of the backfill materials, the type of steel reinforcement, and the details of the newly developed pullout test apparatus.

3.1 Backfill Material

The pullout resistance of reinforcement is influenced by the engineering properties of a backfill material. Granular soils are considered to be suitable backfill for MSE structures because of their high strength, stiffness, and permeability. The AASHTO (2010) *LRFD Bridge Construction Specifications*, the FHWA manual (Elias et al., 2001), and the KDOT (2007) specification specify that all backfill material used in MSE walls shall be free from organic or other deleterious materials and conform to the gradation requirements as provided in Table 3.1. In addition, an angle of internal friction of at least 34 degrees is recommended for select backfill material.

Table 3.1: Gradation Requirements for Select Granular Backfill

U.S. Sieve Size	Percent Passing (Elias et al., 2001)	Percent passing (KDOT, 2007)
4.0 in.	100	100
No. 40	0-60	0-60
No. 200	0-15	0-5

As mentioned in Chapter 1, the objective of this study was to evaluate the effect of aggregate uniformity coefficient on the pullout resistance of ribbed strip reinforcement embedded in aggregates. Six types of aggregates with gradation curves as shown in Figure 3.1 were used for pullout tests, which had uniformity of coefficients of 1.4, 2, 3, 4, 6, and 14, respectively. These aggregates were obtained from the Bonner Spring Quarry, APAC-Kansas, Inc. Particle size distribution tests were conducted to verify their compliance with the recommended gradation requirements. All these aggregates satisfy the AASHTO (2010) MSE wall select granular fill gradation requirements and the KDOT (2007) specification.

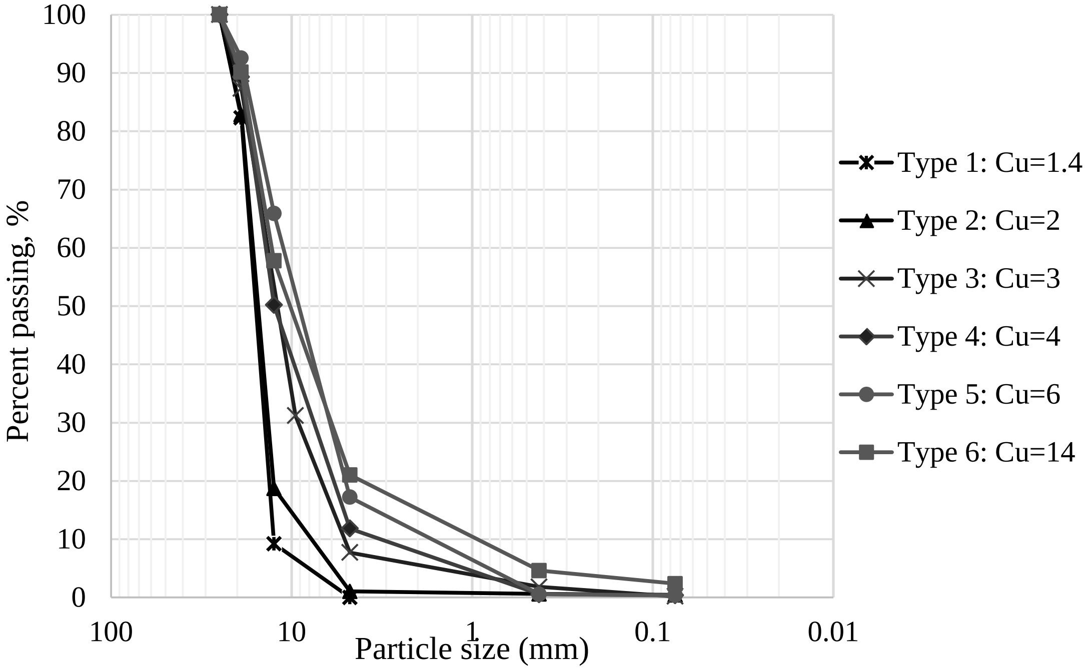


Figure 3.1: Gradation Curves of Backfill Materials

The friction angle of each aggregate backfill was determined using triaxial shear tests. All the backfill materials used in this study were gravelly type. The maximum index density method was initially used to determine the maximum dry densities of the aggregates. However, this method resulted in lower dry densities as compared with those determined by the standard Proctor compaction tests. Considering the fact that aggregates are mostly compacted under a dry condition by vibratory rollers in field, dry compaction densities are more representative to field conditions. Therefore, the maximum dry density of the aggregate determined by the standard Proctor compaction was used to prepare the pullout test samples. However, the minimum dry densities were determined using the minimum index density method. Table 3.2 summarizes the physical properties, the Unified Soil Classification System (USCS) classification, the angle of friction, and the degree of compaction of the aggregates used in the pullout tests.

Table 3.2: Properties and Densities of Backfill Materials in Pullout Tests

Property	**Type 1**	**Type 2**	**Type 3**	**Type 4**	**Type 5**	**Type 6**
Coefficient of uniformity, C_u	1.4	2	3	4	6	14
Coefficient of curvature, C_c	1.0	1.44	1.12	1.04	1.82	2.57
USCS classification	GP	GP	GP	GW	GW	GW
Maximum dry unit weight (pcf)	100	102	109	111	112	118.5
Minimum dry unit weight (pcf)	81	80	85	92	87	95
Angle of friction (deg)	46	49	47	47	49	46
Relative compaction	94	93.5	93.4	94	93	93
Relative density (%)	75	75	75	75	75	70

3.2 Reinforcement

The experimental study evaluated the pullout resistance of galvanized ribbed steel strip reinforcements measuring 5 ft long × 2 inches wide × 0.157 inches thick, which were provided by the Reinforced Earth Company. This strip reinforcement had ribs 0.118 inches high on both the top and bottom of the strip to increase pullout resistance. The effective embedded length, L_e, of the reinforcement used in the pullout test was 4 ft.

3.3 Pullout Test Apparatus

The common approach to evaluate the pullout resistance of soil reinforcements is to use a pullout box. ASTM D6706 (2001) recommends that the minimum dimensions of a large-scale pullout test box should be 24 inches long × 18 inches wide × 12 inches deep. If required, the dimensions of the box should be increased in such a way that the minimum width of the box is greater than 20 times the D85 of the soil or 6 times the maximum soil particle size; the box length should exceed 5 times the maximum size of the geogrid aperture size. In this experimental study, a newly developed pullout box was used. This box was designed and fabricated in the Geotechnical Engineering Laboratory at The University of Kansas, and was designated as the "RJH" pullout box, according to the last initials of the developers (S.M. Rahmaninezhad, Y.

Jiang, and J. Han). The box is made of steel and has inner dimensions of 60 inches long × 24 inches wide × 24 inches high, which exceed those recommended by ASTM. The pullout box has a 1.8-inch-high slot on the front wall. In order to minimize the arching effect during a pullout test, a 6-inch-long sleeve was fixed on the inner side of the front wall and right above the slot. Figure 3.2 shows the new RJH pullout box.

Figure 3.2: RJH Pullout Test Apparatus

In this pullout box apparatus, a uniform normal stress is applied to the embedded earth reinforcement using an air bag. The normal stress simulates the field overburden stress. The pullout load is applied using a double acting hydraulic jack (Model HD-3008) with a maximum capacity of 30 tons, which was manufactured by BVA Hydraulics. This jack is mounted on a steel frame and connected to a main hydraulic pump. The pull force is transmitted to the strip reinforcement through a high tensile strength metal extension rod. The strip reinforcement is connected to the extension rod using a pin mechanism. An S-shape load cell with a maximum capacity of 5 tons is placed next to the hydraulic jack to measure the pullout force.

In this research project, two strain gauge-type displacement transducers, manufactured by Tokyo Sokki Kenkyujo, Co., Ltd., Japan, were used to measure the displacements of the ribbed strip reinforcement. One displacement transducer was fixed at the back end of the strip reinforcement by extending a metal string using a pin connection. The second displacement transducer was mounted on the metal frame that supported the pullout load assembly. The displacement transducers used in this research had two displacement ranges: 0 to 4 inches and 0 to 2 inches. Figure 3.3 shows the setup of the displacement transducers.

Figure 3.3: Setup of Displacement Transducers

Chapter 4: Test Procedure and Data Acquisition

This chapter describes the test procedure and data acquisition system adopted in this study.

4.1 Pullout Test Procedure

The test procedure adopted in this study for pullout tests of ribbed steel strip reinforcement had four steps: (1) test sample preparation, (2) application of normal stress, (3) application of pullout load, and (4) the backfill and the reinforcement were removed from the test box and cleaned up for the next test. This procedure was repeated for each backfill material under one normal stress. In total, 18 pullout tests were conducted, which include six backfill materials under three normal stresses.

4.1.1 Test Sample Preparation

The first step in each pullout test was to prepare a test sample. Preparation of the test sample comprised of filling the test box with the backfill material, placement of a steel strip, compaction of the reinforced backfill, and instrumentation. Proper handling of each procedure of the test sample preparation would significantly affect test results. Thus, great care was given for this step.

The weight of aggregate required to achieve the target density was initially prepared. After that, the backfill material was placed in the box in two lifts. Each lift was compacted using an air backfill tamper with a circular base diameter of 5 inches until the compacted lift thickness of at least 6 inches was attained. Since all the backfill materials used in this study were coarse aggregates (gravel), the sample was compacted until the required degree of compaction was achieved. The appropriate number of passes needed to achieve the required relative density was determined by observation in early stages of the tests. Figure 4.1 shows compaction of the test sample.

Figure 4.1: Compaction of the Test Sample

As shown in Figure 4.2, the strip reinforcement was embedded in the middle of the backfill and attached to the pullout load assembly. The effective embedment length of the reinforcement was measured from the inner edge of the sleeve to the end of the reinforcement. The depth of the backfill above and below the reinforcement was maintained to be at least 6 inches, which met the ASTM recommendation (ASTM D6706, 2001).

Figure 4.2: Ribbed Steel Strip Reinforcement Placed On Top of the First Layer

As part of the test preparation, all the instruments, including the displacement transducers, the load cell, and the pressure gauge, were fixed at their right locations. These instruments, except the pressure gauge, were connected to the data recorders and the computer. Every instrument was inspected to ensure that proper installation was achieved before proceeding to the next steps of the test procedure.

4.1.2 Application of Normal Stress

The normal stress was applied with a pressurized air bag placed on top of the compacted backfill. Air pressure was supplied by the laboratory compressed air system and controlled by the air pressure gauge as shown in Figure 4.3. To create a uniform distribution of normal stress over the backfill, as well as to protect the air bag from damage, a 3-mm-thick geomembrane sheet was placed directly below the air bag. In this study, each type of aggregate was tested under three normal stresses, which represent the typical overburden stresses on strip reinforcement at different elevations in the MSE walls used in Kansas. Accordingly, the three normal stresses chosen for the pullout tests were 3.6, 6, and 10 psi.

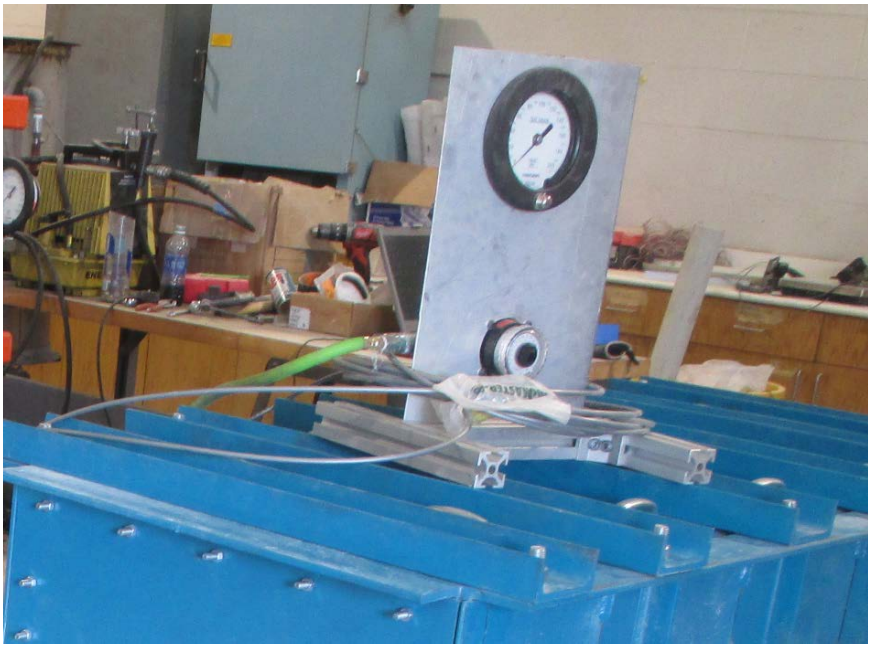


Figure 4.3: Air Gauge for Controlling Normal Stress Application

4.1.3 Application of Pullout Load

Once the normal stress distribution throughout the entire soil mass became stable and the load assembly was set up, the pullout load was applied using a double acting hydraulic jack at a strain rate ranging 0.4 to 0.6 inches/min. The hydraulic jack was connected to a hydraulic pump using two hoses. A check valve was installed to one of the hoses to regulate the pressure applied to the hydraulic jack. Pullout testing of the embedded strip reinforcement was conducted at three different normal stresses for each aggregate backfill.

The applied pullout load and displacements in the two displacement transducers were monitored until ultimate pullout resistance was reached, i.e., the load reading started to decrease considerably. Figure 4.4 shows the pullout load assembly, which consists of the hydraulic jack, the load cell, and the metal pulling rod mounted on the steel frame.

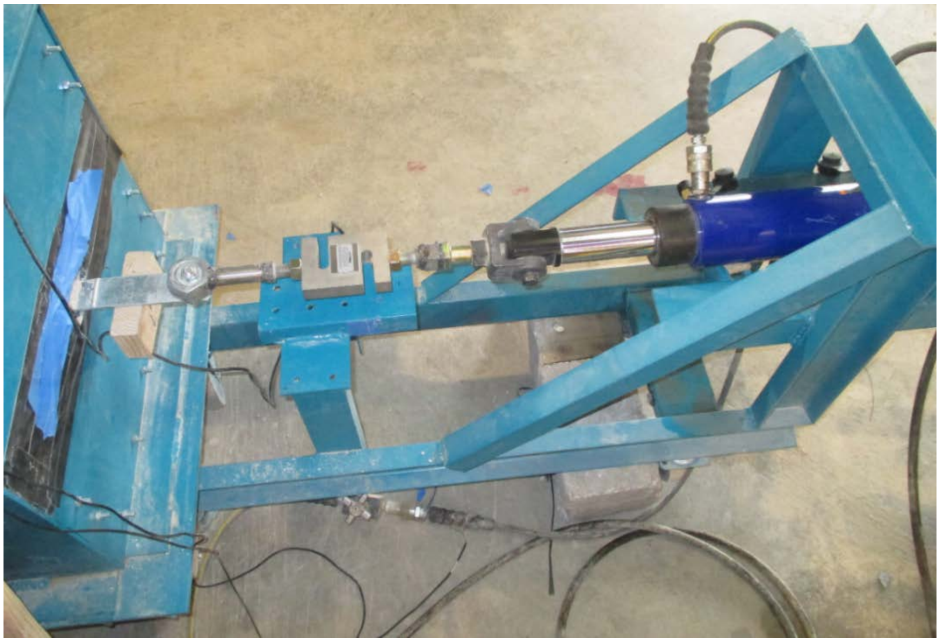


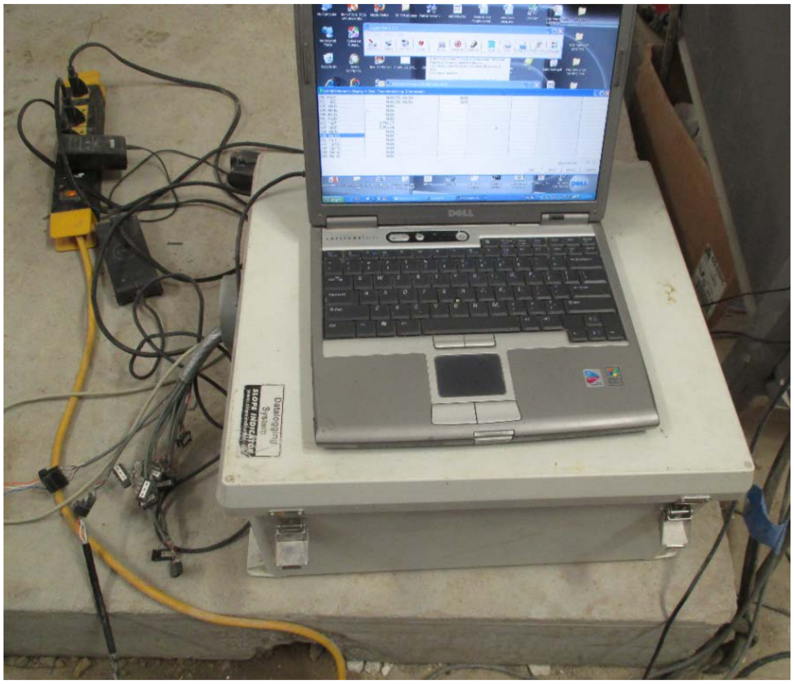
Figure 4.4: Pullout Load Assembly

4.2 Data Acquisition

Once the whole pullout test was set up, all sensors were activated to allow the data acquisition system to start recording data. Data collected during the pullout test included: (1) pullout force, measured with the load cell, (2) normal stress applied to the soil mass, and (3) longitudinal displacements, measured using two displacement transducers.

A Smart Dynamic Strain Recorder DC-204R, manufactured by Tokyo Sokki Kenkyujo, Co., Ltd., Japan, was used to record the data from displacement transducers and load cells. Each recorder had four connection channels to strain gauge sensors. The normal stress applied to the soil mass through the air bag was monitored by the pressure gauge. Figure 4.5 shows the data acquisition system used in this study.

a. Smart Dynamic Strain Recorder, DC-204R



b. Campbell Scientific Data Logging System, CR1000

Figure 4.5: Data Acquisition Systems

Chapter 5: Test Results and Data Analysis

This chapter presents the experimental results from pullout tests performed on ribbed steel strip reinforcements embedded in five different aggregates. In this study, a total of 18 pullout tests were conducted. Each test resulted in a calculated pullout resistance factor, F*, for the particular reinforcement-backfill combination under a specific normal stress. This chapter also includes the comparisons of the calculated F* values from this study with those in the AASHTO (2012) specifications.

5.1 Pullout Force and Displacement

Application of a pullout load generates an outward displacement of a particular reinforcement from soil mass in a pullout test. The ultimate pullout load is often defined as pullout resistance. The displacements of the strip reinforcement were measured at the back and front ends, which were almost identical because of the use of inextensible metallic reinforcement. The front displacement was used for data analysis. After the pullout forces and their corresponding displacements were obtained, they were presented graphically to evaluate the ultimate pullout force. Figures 5.1 to 5.6 show the pullout test results for six reinforcement-aggregate backfill combinations investigated in this study. In each figure, three curves represent the pullout force-displacement relationships under three normal stresses for a given aggregate backfill.

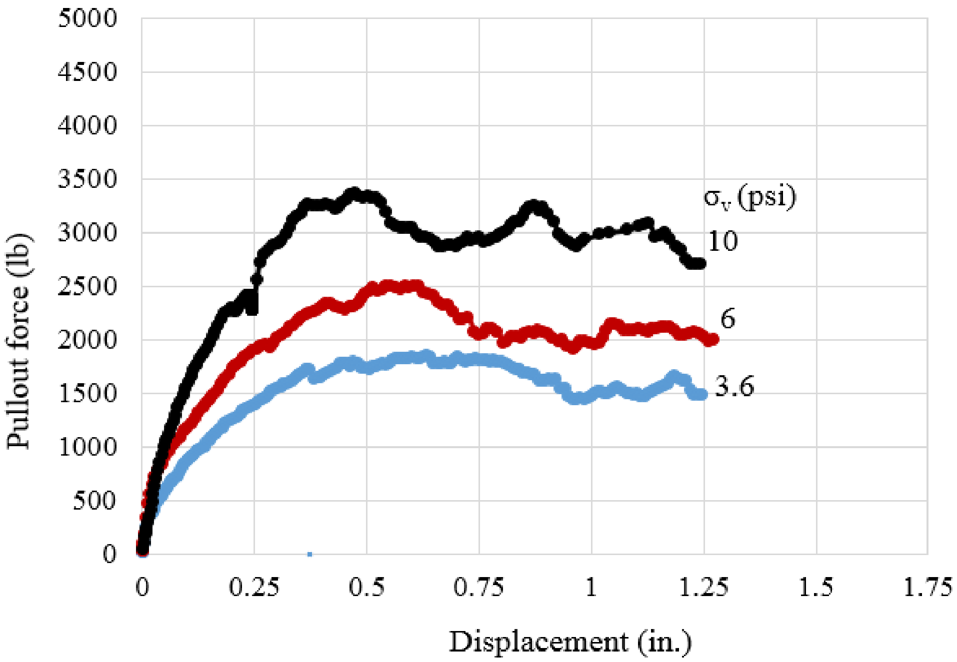


Figure 5.1: Pullout Force versus Displacement Curve for Aggregate with C_u=1.4

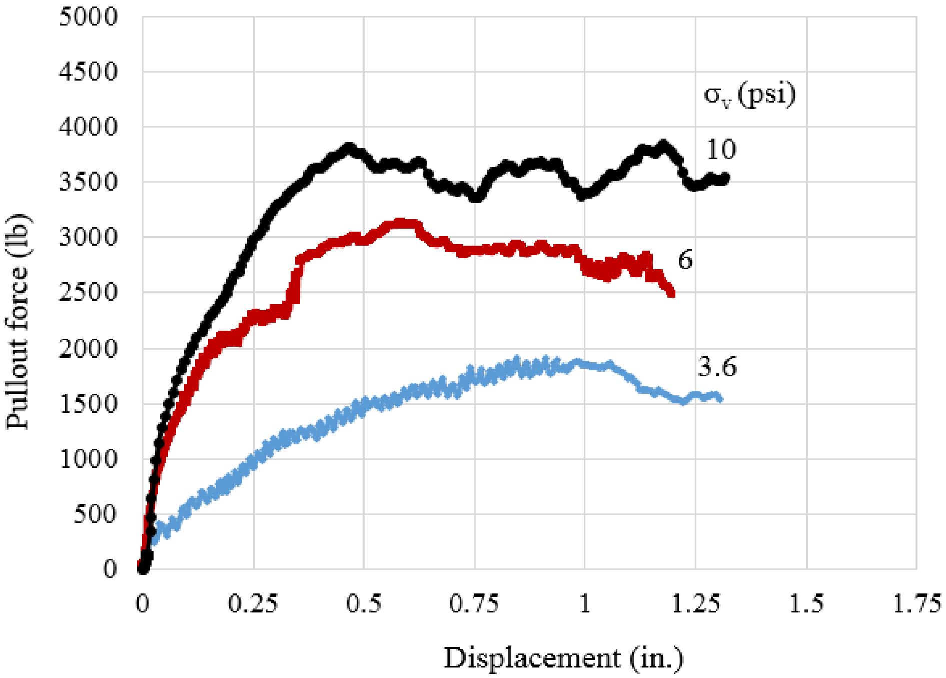


Figure 5.2: Pullout Force versus Displacement Curve for Aggregate with C_u=2

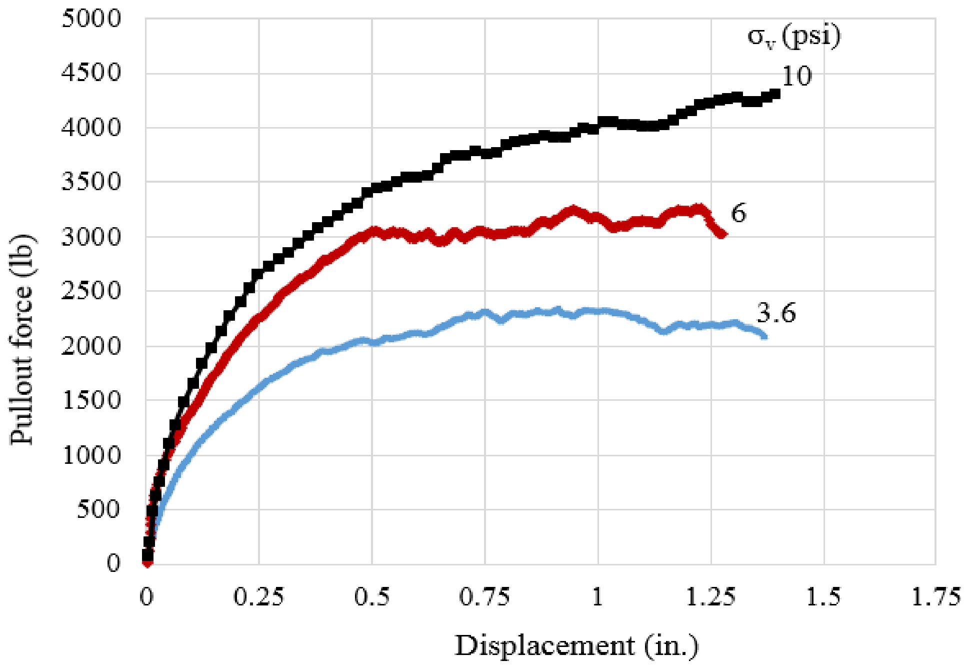


Figure 5.3: Pullout Force versus Displacement Curve for Aggregate with C_u=3

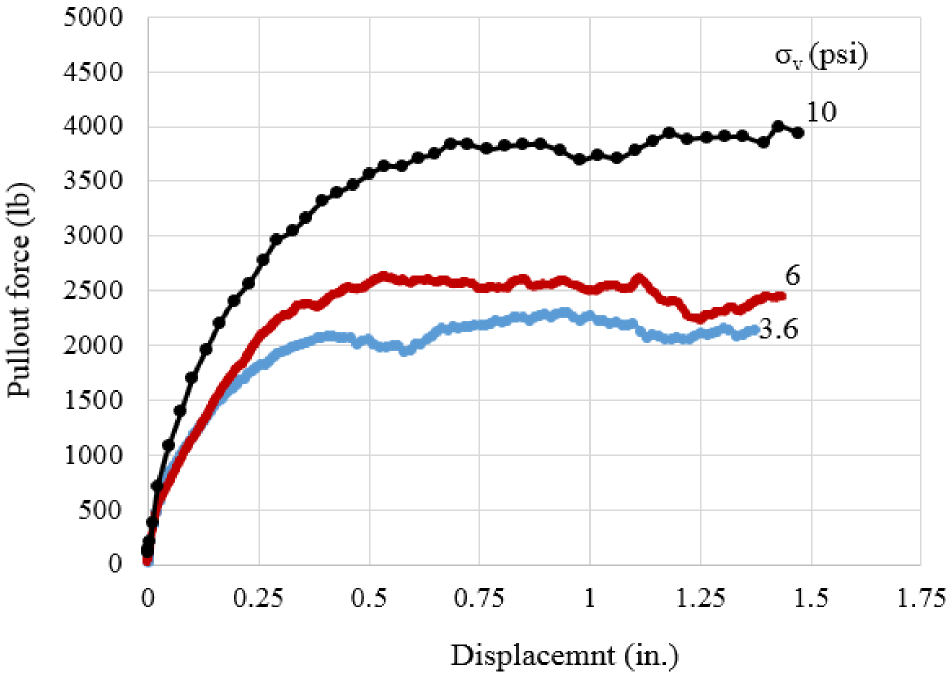


Figure 5.4: Pullout Force versus Displacement Curve for Aggregate with C_u=4

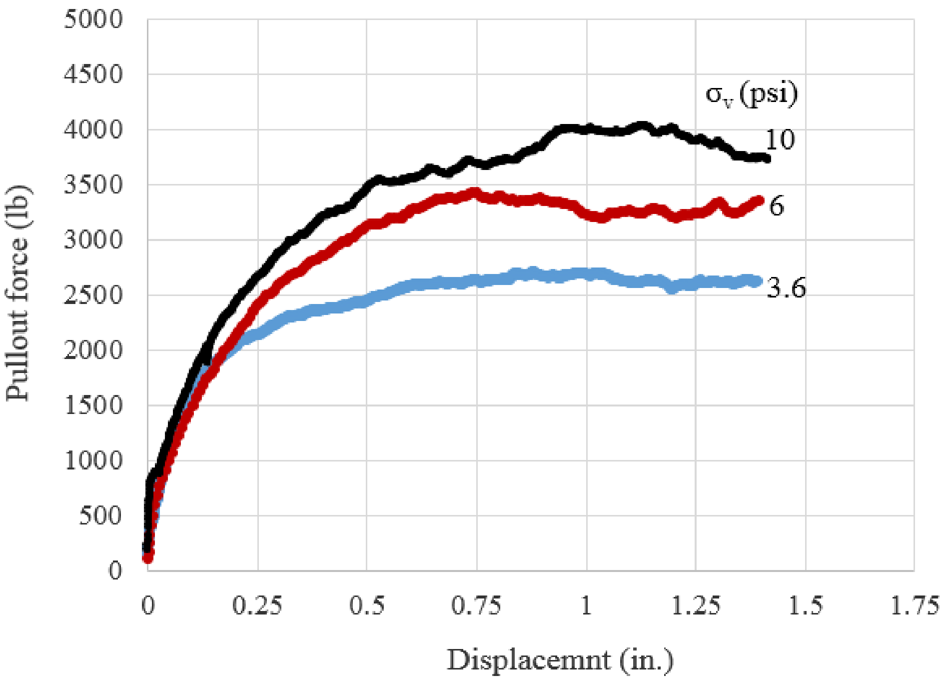


Figure 5.5: Pullout Force versus Displacement Curve for Aggregate with C_u=6

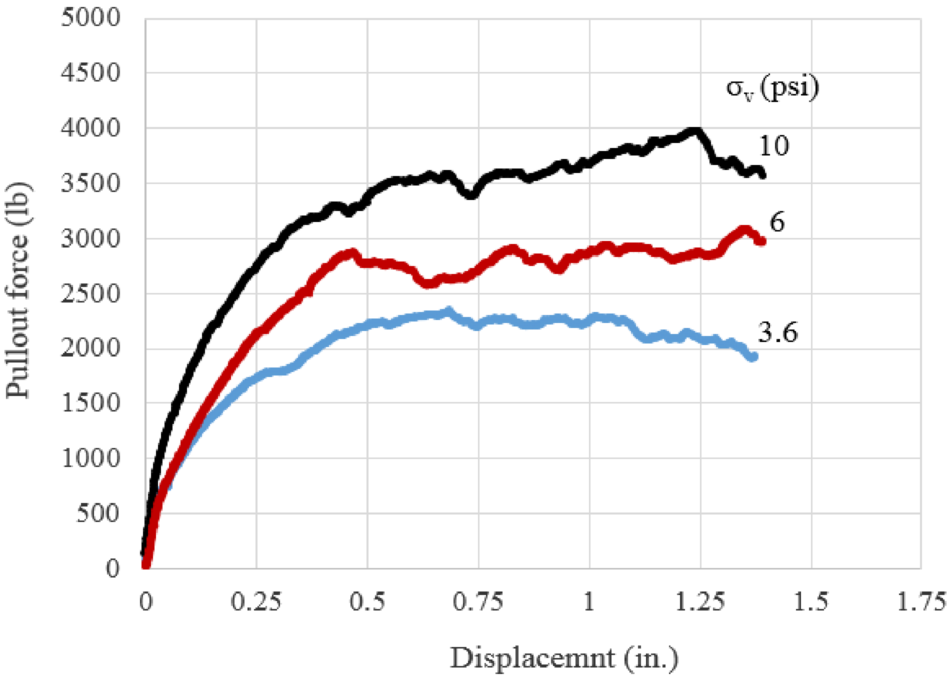


Figure 5.6: Pullout Force versus Displacement Curve for Aggregate with C_u=14

The pullout force-displacement curves presented above had similar trends for a specific applied normal stress. Moreover, for a particular type of aggregate backfill, the pullout resistance increased with the increase in the normal stress. In most of the tests, the displacement at the peak pullout resistance for a given aggregate backfill was insignificantly affected by the normal stress.

Elias et al. (2001) suggested that for inextensible reinforcements, the ultimate pullout resistance should be selected as the pullout force corresponding to the front displacement of ¾ inches, unless the peak resistance occurs first. The need for this allowable displacement criterion is to limit the magnitude of earth structure deformations. The ultimate pullout resistance estimated based on the FHWA guideline was used to calculate the pullout resistance factor, F*, for the all tests in this study.

Figure 5.7 shows the relationship between the applied normal stress and the measured ultimate pullout resistance. It is shown that the ultimate pullout resistance increased with the confining stress. More specifically, for Type 1 (C_u=1.4) and Type 6 (C_u=14) aggregates, the relationships were found to be almost linear.

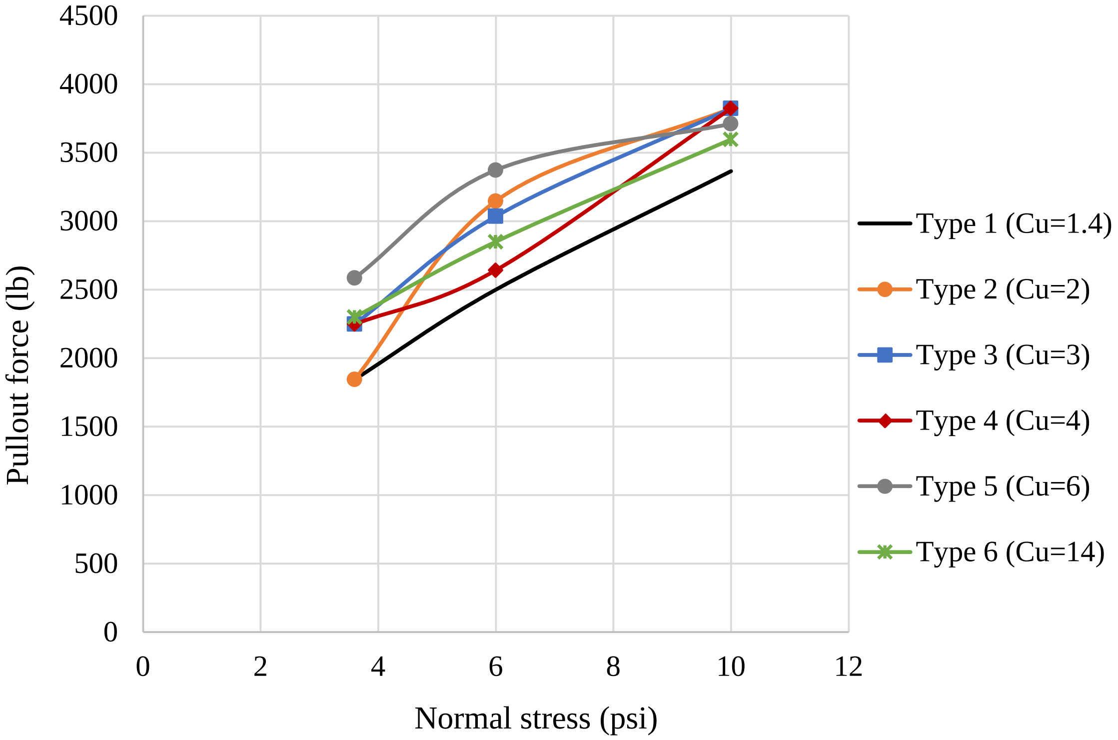


Figure 5.7: Normal Stress-Pullout Force Curves

5.2 Pullout Resistance Factor, F*

The ultimate pullout resistance of a reinforcement can be evaluated using a pullout resistance factor, F*, which combines the overall soil-reinforcement interaction. In this study, the pullout resistance factors, F*, for ribbed steel strip reinforcements were calculated from the test results using Equation 5.1:

$$F^* = \frac{P}{\sigma_v L_e b C \alpha}$$ **Equation 5.1**

Where:

F* = pullout resistance factor

P = ultimate pullout resistance

L_e = effective length of reinforcement in the resisting zone

α = scale effect correction factor (for steel reinforcement, α =1)

σ_v = normal stress at the reinforcement level

C = overall reinforcement surface area geometry factor based on the gross perimeter of the reinforcement (equal to 2 for strip, grid, and sheet-type reinforcements)

In a field project, the normal stress at a certain depth can be estimated as the unit weight of the backfill multiplied by the depth. To analyze the laboratory pullout test results, the corresponding depth of backfill was estimated as the normal stress divided by the unit weight of the backfill. Figure 5.8 presents the F* values obtained from the pullout tests in this study versus the depth of backfill, as compared with the AASHTO reference line for ribbed steel strip reinforcement. AASHTO (2012) suggested that the reference line can only be used for backfill materials with a uniformity coefficient of $C_u \geq 4$. However, Figure 5.8 shows that all the data points from the pullout tests in this study lie considerably far to the right of the AASHTO default F* value line. In other words, the AASHTO default F* values are conservative as compared with the test data, even for the aggregates with a uniformity coefficient of $C_u < 4$. It should be pointed out that the test results in Figure 5.8 had some overlapped data points, which indicate the same F* values for different aggregate backfills at the same normal stress.

For all types of aggregate backfills used in this study, the F* values decreased with the increase in the depth of fill. This trend indicates that the pullout resistance factor of ribbed strip reinforcement depends on the overburden stress. This result is consistent with the AASHTO reference line. Even though the test results have some variations, there is a general implication that the aggregate with a higher uniformity coefficient had higher F* factors than that with a lower uniformity coefficient. The difference in the F* factor between the aggregates with different uniformity coefficients became less when the depth of fill got larger. The F* factors for different aggregates at the depth of fill equal to 14 ft (i.e., 10 psi) were almost the same.

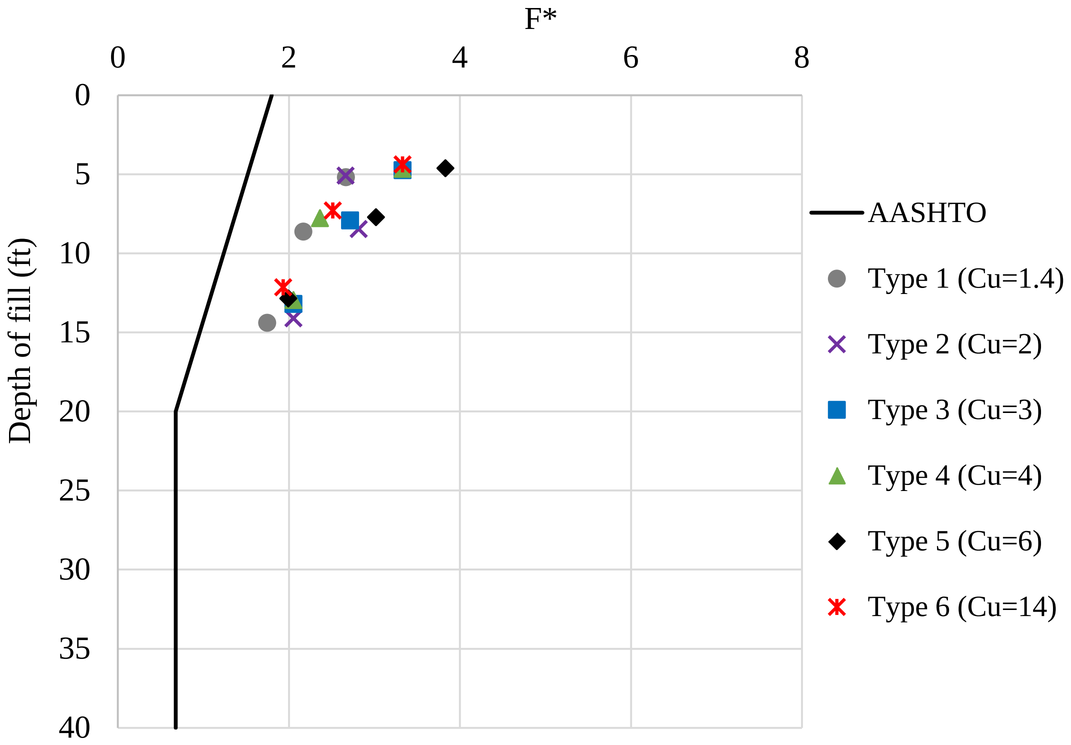


Figure 5.8: F* Values for Ribbed Steel Strip Reinforcement in Aggregate Backfills

Chapter 6: Conclusions and Recommendations

The objective of this study was to verify the AASHTO (2012) formula or develop a new one that is applicable for estimating pullout resistance of steel strip reinforcement embedded in uniform aggregates available in Kansas quarries. To achieve this objective, 18 large-scale pullout tests were conducted to investigate the effect of aggregate uniformity on the pullout resistance of ribbed steel strip reinforcement in six aggregates with uniformity coefficients ranging from 1.4 to 14. The following conclusions and recommendations can be made based on the experimental study.

6.1 Conclusions

1. Pullout test results showed that ribbed steel strip reinforcement in all types of aggregates had similar overall trends of pullout force versus displacement curves. At a lower normal stress (i.e. 3.6 psi), the steel reinforcement in the aggregate with the lowest uniformity coefficients (C_u=1.4 and 2) had the lowest pullout resistance. At a higher normal stress (i.e. 10 psi), however, all aggregates except Type 1 (C_u=1.4) resulted in nearly the same pullout resistance. In other words, the aggregate uniformity had more effect on the pullout resistance at a lower normal stress than that at a higher normal stress for all aggregates but Type 1.
2. The test results showed that the ultimate pullout resistance for ribbed steel strip reinforcement increased with the overburden depth, whereas the pullout resistance factor, F*, decreased with depth.
3. The pullout resistance factors for all reinforcement-backfill combinations determined in this study are higher than the default F* values for ribbed strip reinforcement recommended by AASHTO (2012). This comparison indicates that the F* values recommended by AASHTO are conservative for ribbed steel strip reinforcement in aggregate backfills, even for the backfill of a uniformity coefficient as low as 1.4.

6.2 Recommendations

1. The AASHTO default F* line for ribbed steel strips is limited to select backfills with a uniformity coefficient of $C_u \geq 4$. Based on the test results in this study, the aggregate uniformity had some effects on the calculated F* value at a lower normal stress, but its effect became minimal at a higher normal stress. Since the AASHTO default F* line is conservative for aggregates with the uniformity coefficient of $1.4 < C_u < 4$ or $C_u > 4$, it can be used for the aggregates with the uniformity coefficient of $C_u > 1.4$, provided the aggregate satisfies the standard backfill gradation requirements.
2. The conclusions obtained from this study are based on ribbed steel reinforcement in aggregate backfill. Further studies are needed to verify these conclusions for other type of steel reinforcement and backfill.

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Appendix A: Backfill Material Gradation

Table A.1 presents the particle size distributions of the five aggregate backfills used in this experimental study. The FHWA and KDOT gradation requirements are also included in this table for comparison and verification.

Table A.1: Aggregate Backfills Gradation Summary

Sieve Size			**Percent passing (%)**					
	FHWA	**KDOT**	**Type 1**	**Type 2**	**Type 3**	**Type 4**	**Type 5**	**Type 6**
4 in.	100	100	-	-	-	-	-	-
1 in.	-	-	100	100	100	100	100	100
3/4 in.	-	-	82.4	82.9	87.4	89.3	92.5	90.1
1/2 in.	-	-	9.5	18.7	31.2	50.2	65.9	57.8
No. 4	-	-	0	1.0	7.7	11.8	17.2	21.0
No. 40	0-60	0-60	-	0.6	1.8	0.6	0.5	4.6
No. 200	0-15	0-5	-	0.4	0.2	0.4	0.4	2.4
C_u	-	-	1.4	2	3	4	6	14

Appendix B: Triaxial Test Results

Triaxial tests were performed on all aggregate backfills under three confining stresses (10, 15, and 20 psi). The friction angles were found to be within a range of 46-49°. Figures B.1 to B.12 show the stress-strain curves and the Mohr circles at the normal stresses corresponding to 5% strain for the six types of aggregates.

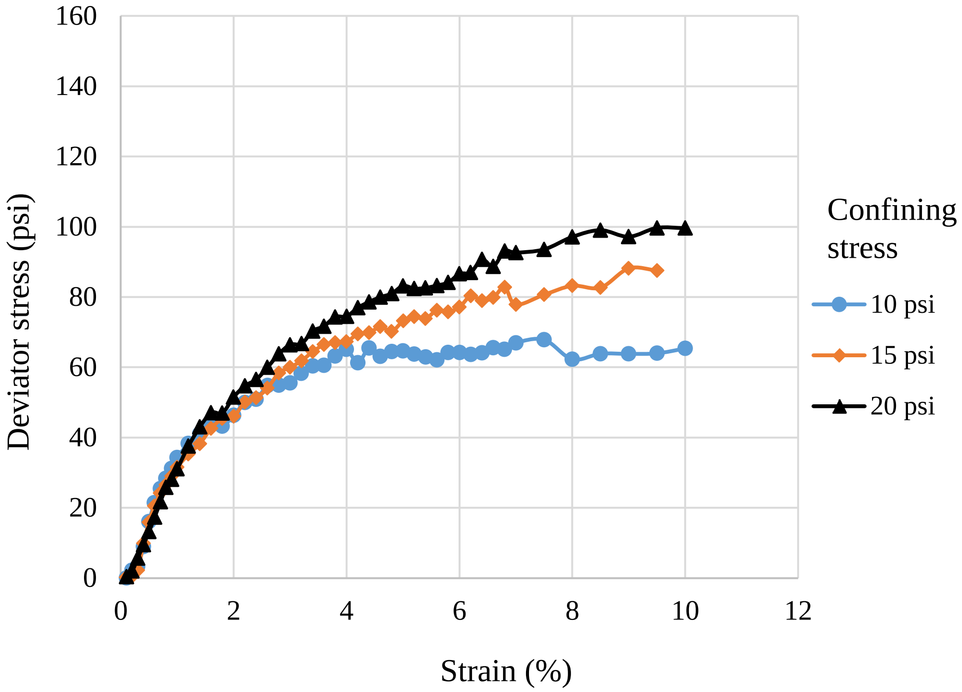

Figure B.1: Stress-Strain Curves for C_u=1.4

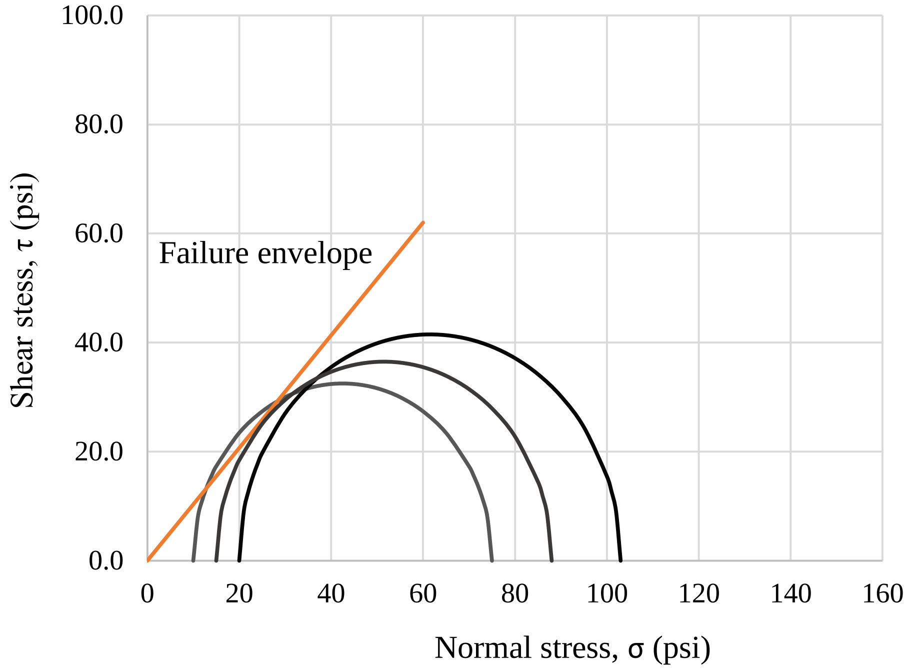

Figure B.2: Mohr Circles for C_u=1.4

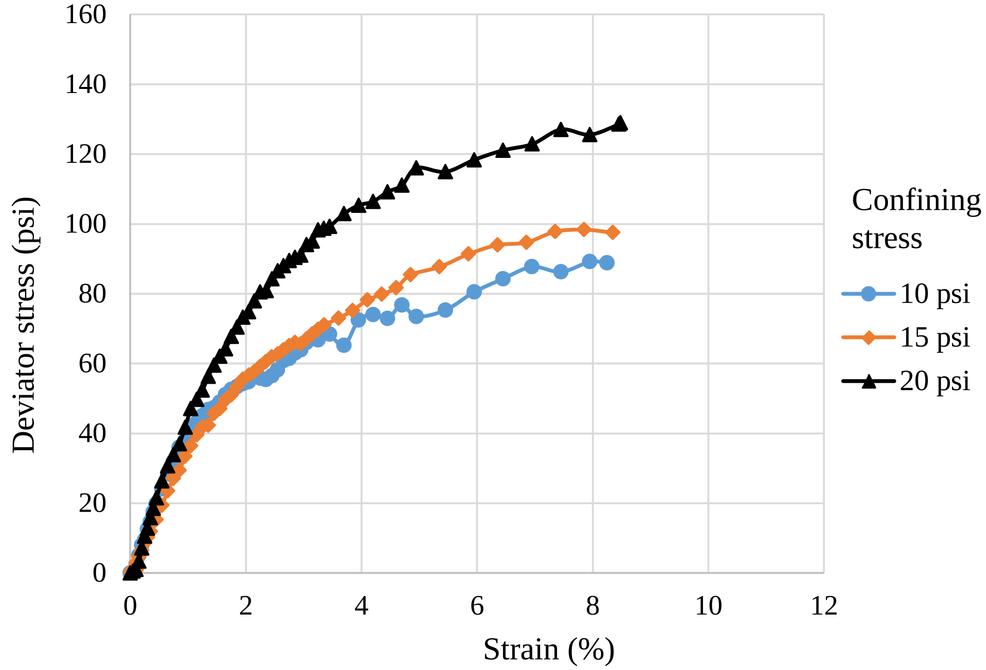

Figure B.3: Stress-Strain Curves for C_u=2

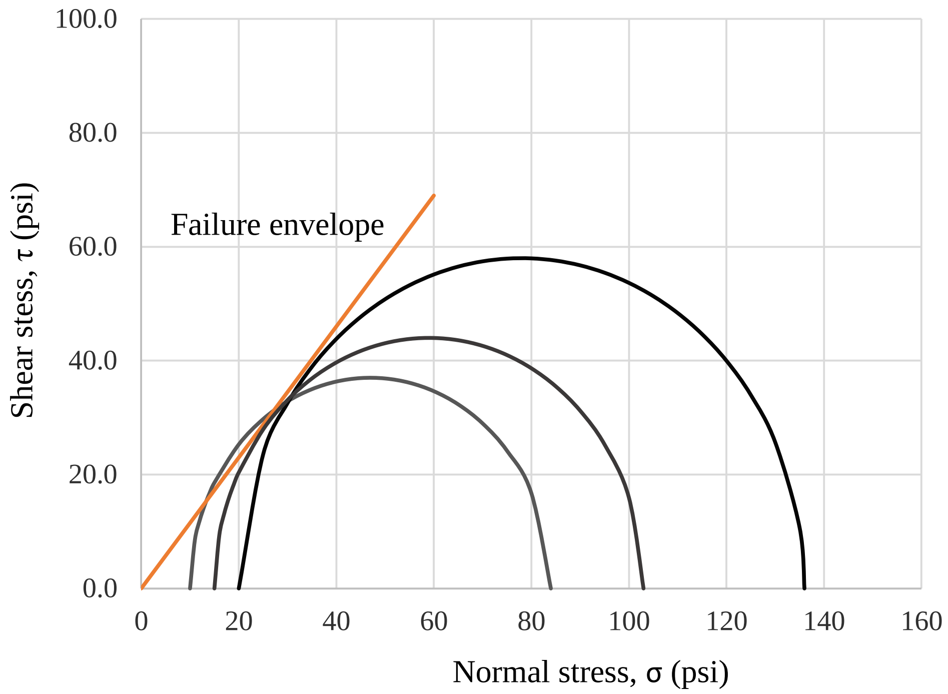

Figure B.4: Mohr Circles for C_u=2

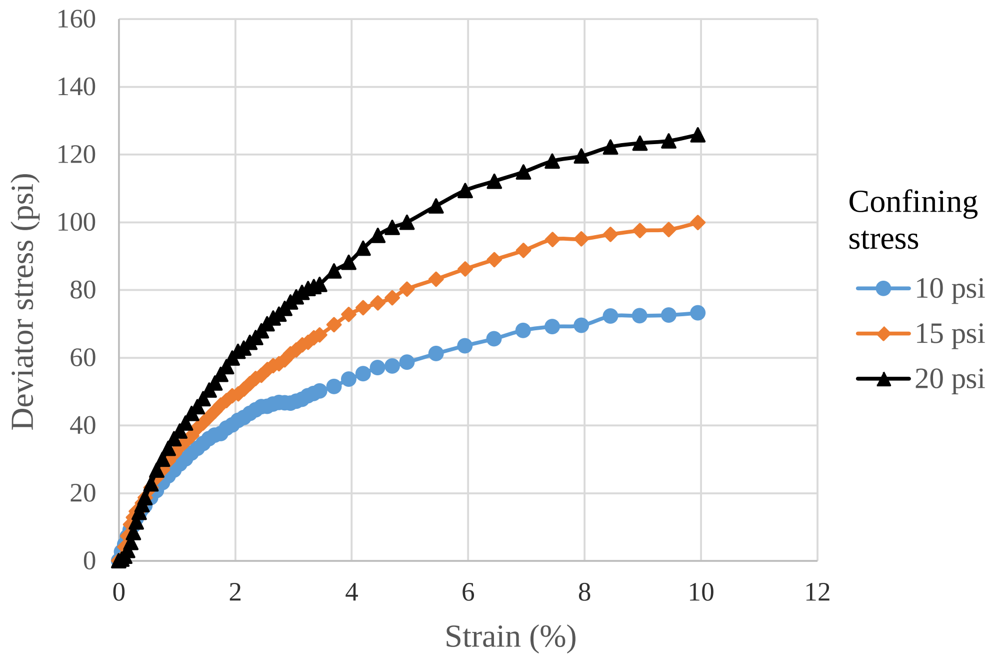

Figure B.5: Stress-Strain Curves for C_u=3

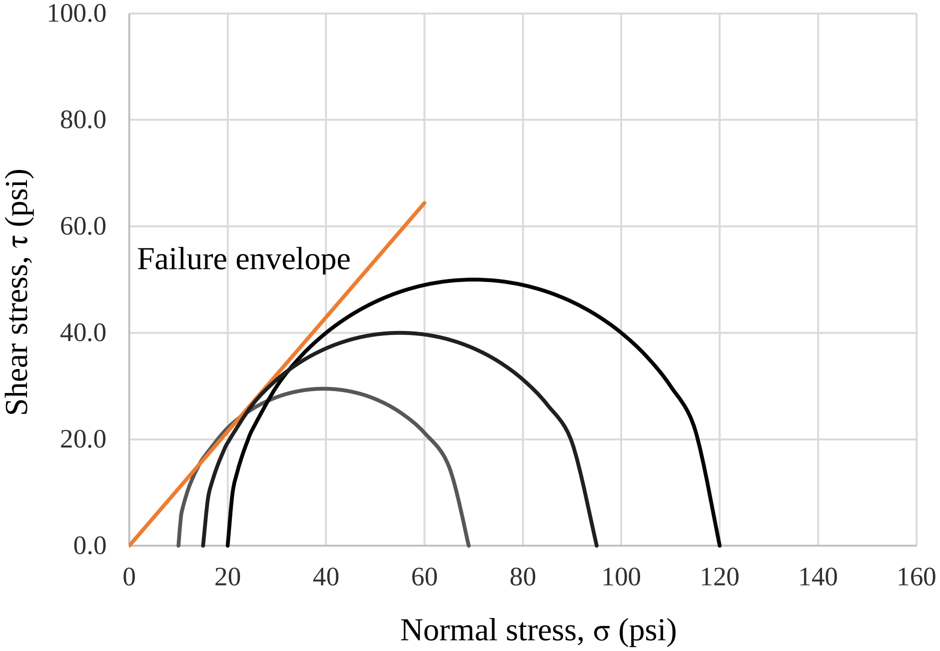

Figure B.6: Mohr Circles for C_u=3

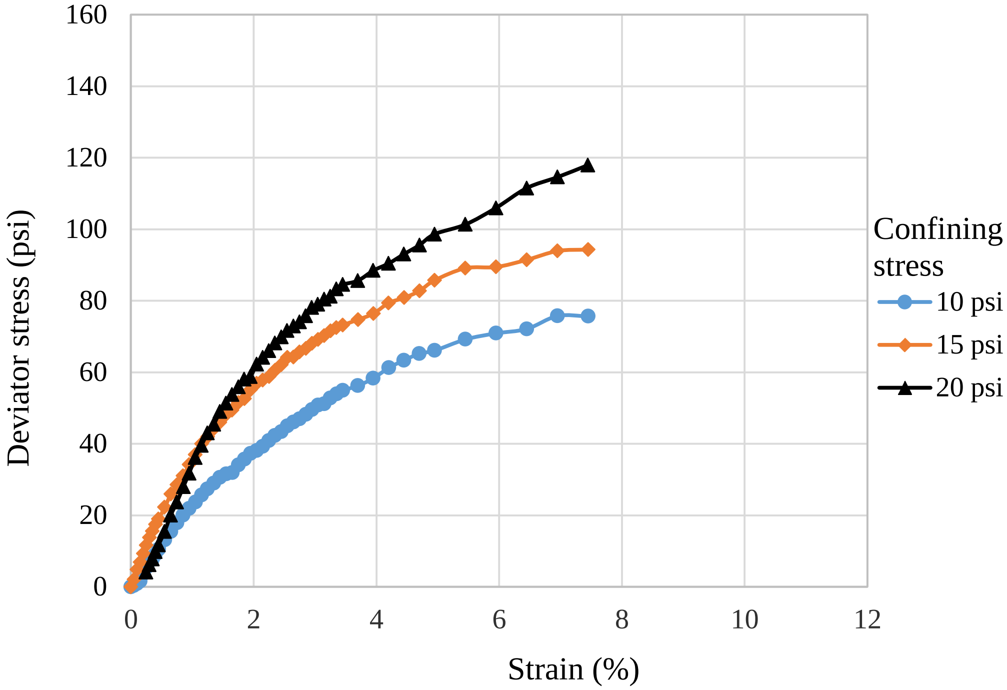

Figure B.7: Stress-Strain Curves for C_u=4

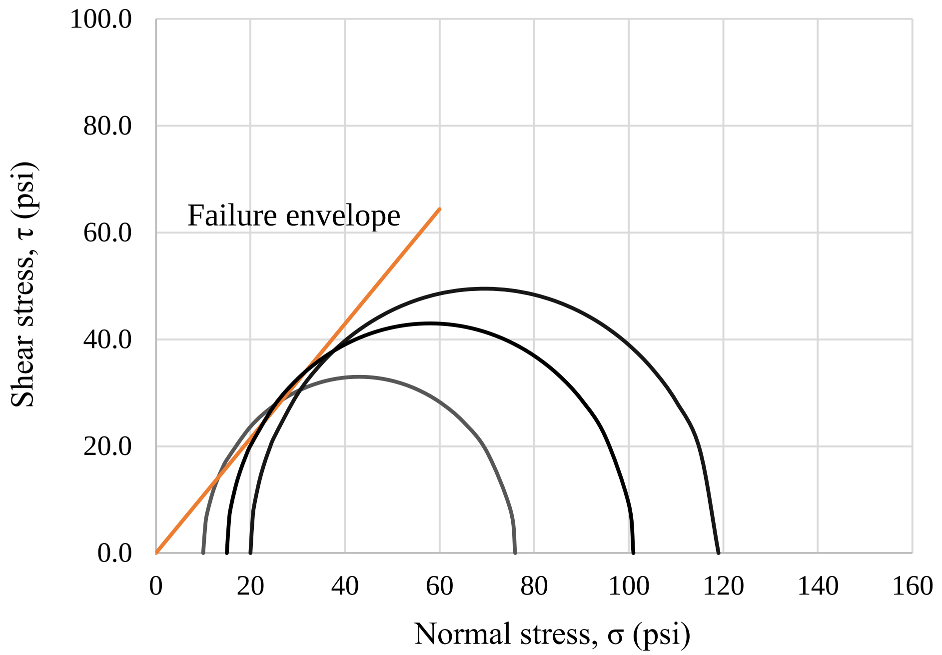

Figure B.8: Mohr Circles for C_u=4

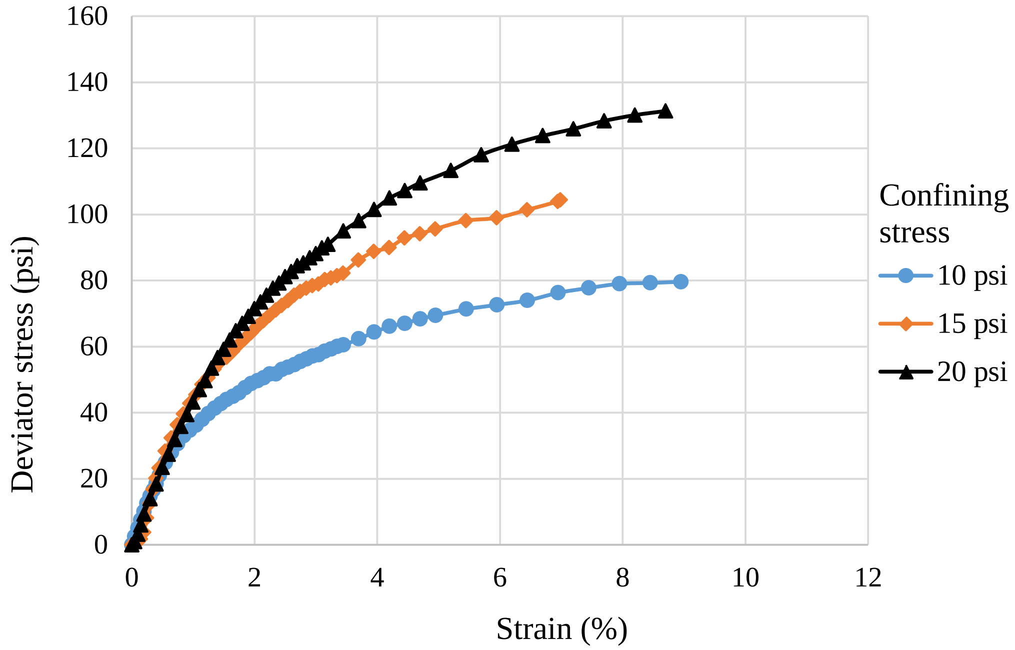

Figure B.9: Stress-Strain Curves for C_u=6

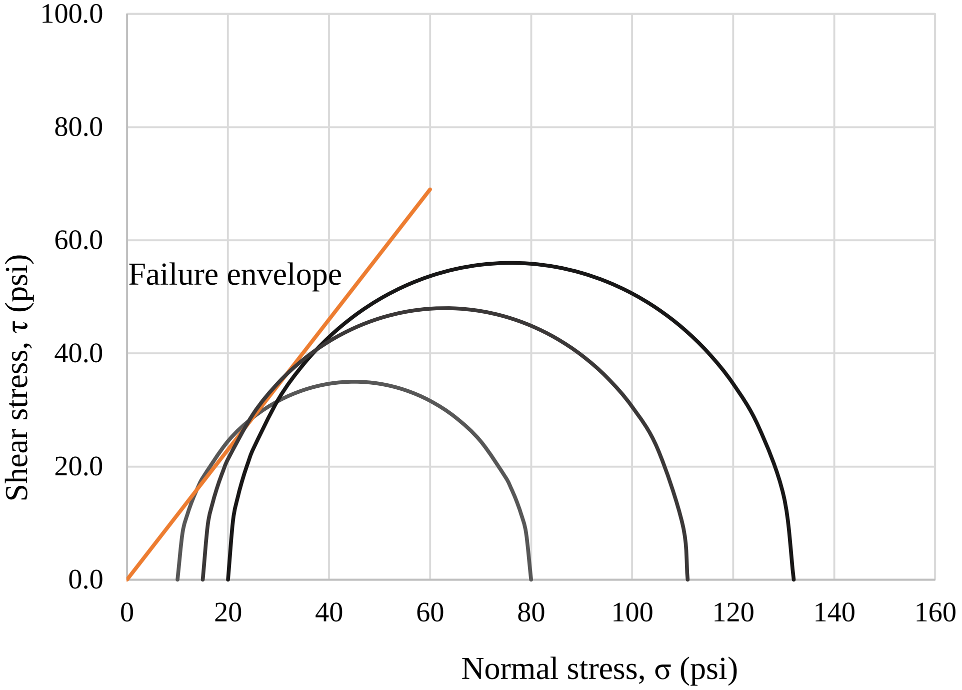

Figure B.10: Mohr Circles for C_u=6

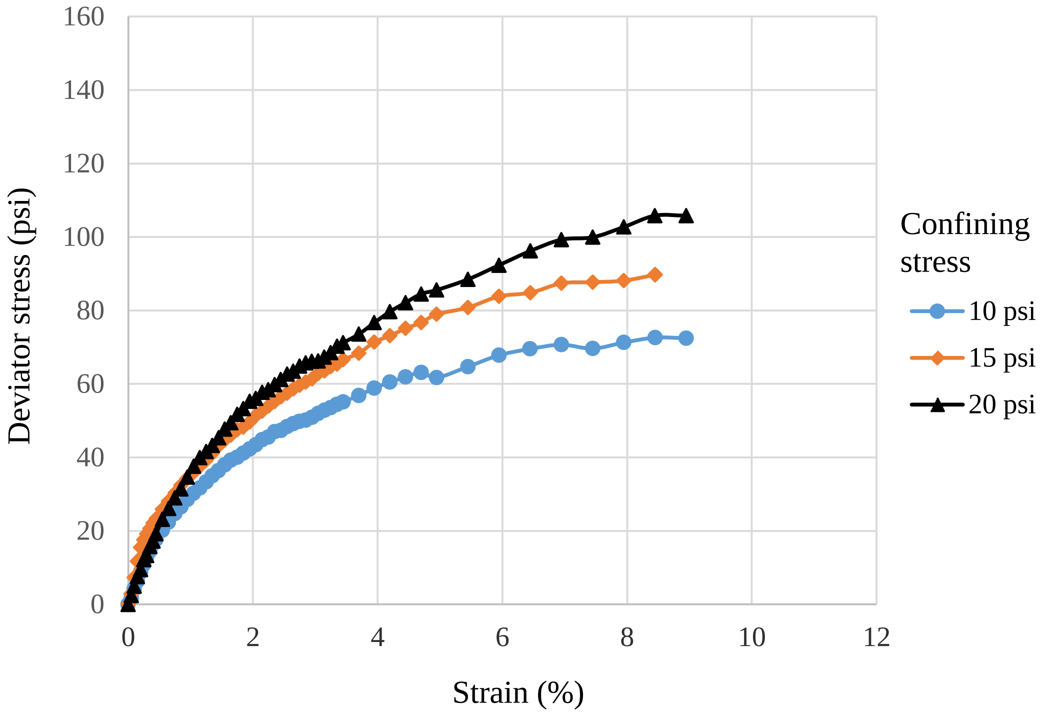

Figure B.11: Stress-Strain Curves for C_u=14

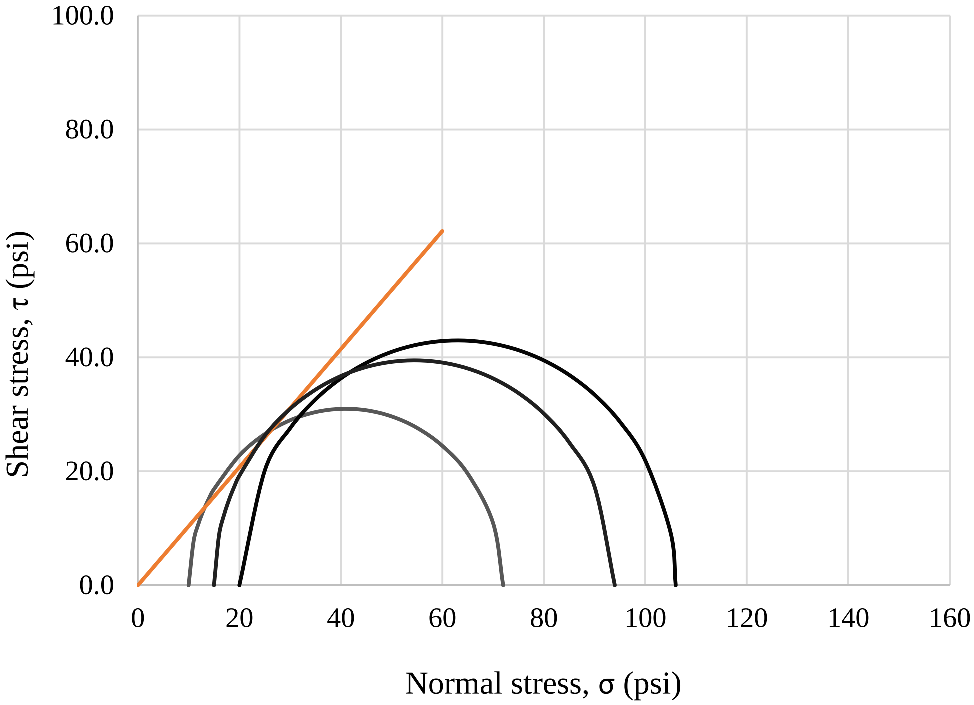

Figure B.12: Mohr Circles for C_u=14

Appendix C: Pullout Test Summary

The test data provided in Table C.1 were used to calculate the pullout resistance factors, F*.

Table C.1: Summary of Pullout Test Data

Backfill Type	Uniformity coefficient, C_u	Effective length, L_e (in.)	Width, b (in.)	Displacement (in.)	Normal stress, σ_v (psi)	Depth of fill (ft)	Pullout force, P_r (lb)	F*
1	1.4	48	2	0.63	3.6	5.2	1845	2.67
				0.6	6	8.6	2500	2.17
				0.47	10	14.4	3365	1.75
2	2	48	2	0.75	3.6	5.1	1800	2.67
				0.6	6	8.5	3147	2.82
				0.47	10	14.1	3823	2.06
3	3	48	2	0.75	3.6	4.8	2248	3.33
				0.75	6	7.9	3035	2.72
				0.75	10	13.2	3823	2.06
4	4	48	2	0.75	3.6	4.7	2248	3.33
				0.53	6	7.8	2643	2.37
				0.67	10	13	3823	2.06
5	6	48	2	0.75	3.6	4.6	2585	3.83
				0.75	6	7.7	3373	3.02
				0.75	10	12.9	3710	2.00
6	14	48	2	0.7	3.6	4.4	2300	3.33
				0.47	6	7.3	2850	2.54
				0.7	10	12.2	3597	1.94

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